MRI of the Heart and Vessels
Massimo Lombardi • Carlo Bartolozzi

MRI of the Heart and Vessels

Foreword by

Luigi Donato

Springer
Foreword

This reference book on the use of Magnetic Resonance in the study of the heart and vessels by Massimo Lombardi and Carlo Bartolozzi represents an excellent opportunity for meditation and discussion on some of the present trends in clinical medicine.

The first consideration cannot but concern the rapid and continuing evolution of diagnostic technologies, and particularly of those in the field of imaging: a topic that only ten years ago would never have even been considered as a subject for a book of this type, but that today clearly offers evidence of a concrete and relevant contribution, in some cases exclusive, to many applications of cardiovascular diagnostics. From this point of view, the authors deserve particular recognition for having put together a synthesis and a critical presentation of the many applications in the field of Magnetic Resonance Imaging: a contribution that will be of sure interest to the consultants and specialists of imaging techniques and of medical and surgical cardiovascular disciplines.

The second consideration concerns the fundamental importance of the integration of medical and non-medical competencies in the development and management of new technologies in medicine. In sectors such as MRI the collaboration between physicists and engineers not only provides a promise for the correct exploitation of the techniques but also, and perhaps especially, a basis for the very same development of the clinical applications in a sector in which the boundaries between development and application are far from established and indeed in continuous evolution.

The third consideration concerns the importance of the collaboration between the Institute of Clinical Physiology and the departments of University hospitals: the first institution being deeply characterized by the mission of performing clinical research through a broad multi-disciplinarian basis, closely integrated with on-field clinical applications, which validate innovations providing the drive for further research; the second institution characterized by the important task of specialized training and assistance, the quality of which must necessarily be guaran-
teed and renewed on the basis of the progress of technological knowledge.

My last consideration addresses the importance in the management of continuously evolving technological innovations, through a sound relationship between industrial companies and research institutions that goes far beyond bare commercial aims.

For all the considerations above, this book represents a precious and very significant example, which I am very glad to present.

Finally, I wish to express my particular appreciation to Massimo Lombardi and the entire medical and non-medical staff, nursing, technical and administrative personnel of the Magnetic Resonance laboratory of the IFC-CNR, who have, in less than four years of intense activity – often in difficult working conditions – developed an idea into a consolidated reliable, reality, and have especially demonstrated the ability of the laboratory to be at the cutting age of this developing field.

Pisa, December 2004

Luigi Donato
Head of CNR
Institute of Clinical Physiology, Pisa
Preface

The study of the heart and vessels by Magnetic Resonance Imaging represents a relatively new field of application, especially if one considers the large-scale diagnostic use of the technique in the neurological and muscular fields.

The explanation of the delayed application in the cardiovascular field can be sought in the methodological complexity linked to the study of moving anatomical structures.

Due to the important developments in terms of hardware and software seen in recent years, we can now choose a dedicated approach for the study of the heart and vessels that allows us to achieve all that morphological and functional information that otherwise could not have been obtained by means of other imaging techniques.

This monographic text originates from the collaboration of two disciplines that have historically covered specific interests in clinical-diagnostic and technical-applicative settings: Cardiology and Radiology.

The heart and vessels, which have often represented a battle ground, have been for our Groups, fertile ground for development of competencies, driven by our firma belief that a multidisciplinary approach represents the most efficient way to exploit technological resources to the best and respond in the best manner to clinical needs.

Although this is a subject in continuous and rapid evolution, we wanted to dedicate the first part of this text to some particular methodological/technical aspects concerning the techniques of fast acquisition finalized toward the achievement of morphological, functional, and flow related information. The same section deals with contrast agents that nowadays represent an integrating part of the exam, with particular focus on the optimization of their use.

The last chapter of the introductive part is dedicated to image post processing; we present the techniques that are at present indispensable for obtaining a better interpretation of the native images and allow at the same time quantitative-qualitative evaluations facil-
ilitating the correlation with data obtained by other techniques of cardiovascular imaging.

The most extensive part of this book is dedicated to clinical diagnostic applications.

In reference to cardiology, we present the contribution of MRI in the most consolidated clinical sectors, providing an updated reference of positive practical value. At the same time we have wanted to analyze, in a prospective way, the most interesting applicative evolutions of what we foresee will find wide diffusion throughout cardiological diagnostics in the near future.

The second clinical diagnostic topic is represented by the study of the vessels: the subject has been approached to the full, spanning from the intracranial vasculature to the peripheral vessels of the limbs, in consideration of the panexplorative characteristics of MRI.

Wide space has also been dedicated to images, in order to allow the reader an immediate correlation of the description of the methods and disease on one hand, and the iconographic representation on the other.

This result has been achieved thanks to the Editor, who has permitted a full range of action as to the number of images reproduced and has assured us the best of quality. We are confident this aspect will be appreciated by those wishing to use this book as a reference text for the use of MRI in the cardio-vascular setting.

Pisa, December 2004

Carlo Bartolozzi
Director
Diagnostic and Interventional Radiology
University, AOUP, Pisa
A special message of acknowledgments to my colleagues involved in such a cumbersome task as the one we have just accomplished, an address that is more a letter of apology. Acknowledgements, which are even more due, as they have not been requested and perhaps arrive even unexpected.

In reality, along with the exciting scientific experience implicit to the preparation of a book of this type, there are surprising human aspects. During the argumentations born from different experiences, sometimes passionate, which dragged beyond dawn, the most sincere and spontaneous character traits were unveiled. The surprising aspect lies in the very enthusiasm and the constant tension my colleagues have shown throughout this journey from the planning to the printing of this book. This engagement added to the already many clinical, diagnostic, and professional duties, that seemingly would have left no spare time to any further workloads. What was unveiled to my eyes during these months can be summarized in two main aspects. The first is the enthusiasm towards a live, fulfilling – but also demanding – technique. The second aspect, which is quite flattering, is the friendship and availability shown by all the Authors to the Editors and especially to myself.

A special thanks goes to the technical, nursing, engineering and secretarial staff of the MRI laboratory of the IFC-CNR of Pisa, and in the same degree to the Diagnostic and Interventional Radiology Department of the University of Pisa that have allowed me to add further turbulence to the already chaotic daily activity without showing the slightest sign of restlessness or surrender, rather inspiring me to an even greater effort.

A special acknowledgment also to prof Alessandro Distante for his constant support, and to prof Antonio L’Abbate for his elegant and indulgent patience.

It must be remembered that this book would have lost, in terms of clarity, if I had not been assisted by the editorial staff of Springer-Verlag Italia, whose members have succeeded in interpreting many illogic statements and incongruities, which are overwhelming in a
publication of this kind, notwithstanding the cryptic technical jargon. The attitude of the publishing, highly competent and collaborative staff was actually pleasant and made the technical decisions arising from the many technicalities in the transition from the manuscript to the definitive print easy.

A very special acknowledgment has to be reserved to Manuella Walker who has shown during these months the right mixture of patience, scientific curiosity, and friendly availability, which was necessary to translate the text into English according to the Authors’ requests.

Lastly, I owe an apology to my family who watched over me with love and understanding in virtue of purely humanistic motivations, leaving me to my guilty absence.

I hope that the reader – if there will ever be one – will recall while judging this book, at least for a moment the hard work of all those who have made the publishing possible.

Pisa, December 2004

Massimo Lombardi
Director MRI Laboratory
CNR, Institute of Clinical Physiology, Pisa
Contents

1 Physical principles of imaging with magnetic resonance .......... 1
   Maria Filomena Santarelli

   1.1 Introduction ................................................................. 1
   1.2 The phenomenon of magnetic resonance ......................... 1
   1.2.1 The nucleus ............................................................ 2
   1.3 Interaction with an external magnetic field ...................... 3
   1.3.1 Radio Frequency (RF) pulses .................................... 4
   1.3.2 Free Induction Decay (FID) ...................................... 5
   1.4 Magnetic Resonance interaction with tissues .................... 7
   1.4.1 Proton density ........................................................ 7
   1.4.2 Relaxation ............................................................. 7
   1.4.3 RF pulse sequences ................................................ 9
   1.4.4 MR signal parameters ............................................. 13
   1.5 MR imaging ............................................................. 16
   1.5.1 Magnetic field gradients ........................................ 17
   1.5.2 K-space ............................................................... 21
   1.6 From K-space to the MR image:
   the Fourier Transform ............................................... 23
   1.7 MRI hardware .......................................................... 23
   1.7.1 The magnet ......................................................... 24
   1.7.2 Radio frequency coils ............................................ 26
   1.7.3 Field gradient ...................................................... 27
   1.7.4 Computer ........................................................... 28

References .............................................................................. 28

2 Techniques of fast MR imaging for studying
   the cardiovascular system ................................................. 31
   Maria Filomena Santarelli

   2.1 Introduction ................................................................. 31
   2.2 Methods for optimizing K-space covering ...................... 31
   2.2.1 Scanning time ....................................................... 31
   2.2.2 Cardiac Gating ..................................................... 33
   2.2.3 Partial filling of K-space ....................................... 35
   2.2.4 Segmentation ....................................................... 37
   2.2.5 Single pulse ......................................................... 38
4.4 Intracellular or organ-specific contrast agents ................. 83
4.5 Guide to the use of contrast agents in cardiovascular magnetic resonance ......................................................... 83
4.6 Toxicity of contrast agents in magnetic resonance ........................................................ 84
4.7 Way of administration ...................................................... 85
References .................................................................................. 85

5 Intracranial vascular district ..................................................... 89
Raffaello Canapicchi, Francesco Lombardo, Fabio Scazzeri, Domenico Montanaro

5.1 Introduction ........................................................................ 89
5.2 Arterial compartment ........................................................... 89
5.2.1 Anatomical variants and persistence of fetal anastomoses 89
5.2.2 Arterial lumen abnormalities: steno-occlusion and ectasia 90
5.2.3 Vascular malformations .................................................... 98
5.2.4 Aneurysms ................................................................... 105
5.2.5 Neurovascular conflict .................................................... 110
5.2.6 Expansive lesions (dislocations and neoformed vascularizations) ...................................................... 111
5.3 Venous compartment ............................................................ 111
5.3.1 Occlusive pathology ....................................................... 111
5.3.2 Venous angiomas ........................................................... 115
5.3.3 Tumors (relationship with main venous structures: surgical planning) ...................................................... 115
References .................................................................................. 116

6 Vessels of the neck ................................................................... 121
Mirco Cosottini, Maria Chiara Michelassi, Guido Lazzarotti

6.1 Introduction ........................................................................ 121
6.2 Imaging techniques ............................................................ 121
6.3 Evaluation of epi-aortic vessels ........................................... 122
6.4 Subclavian arteries .............................................................. 123
6.5 Carotid and vertebral arteries ............................................. 127
6.5.1 Atherosclerotic steno-occlusive disease ......................... 127
6.5.2 Non-atherosclerotic pathology ........................................ 136
References .................................................................................. 141

7 Heart ...................................................................................... 145
7.1 Heart morphology ............................................................... 145
7.1.1 Introduction .......................................................... 145
7.1.2 Study of heart morphology .................................... 145
7.1.3 Scanning and segment planes of the heart ............... 146
7.1.4 Strategy of image acquisition .................................. 149
7.1.5 Techniques for measuring wall thickness and cardiac diameters .................................................. 152
7.1.6 Advantages and limitations .................................... 153
References......................................................................... 154

7.2 Study of heart function .............................................. 154
    Anna Maria Sironi, Massimo Lombardi, Alessia Pepe, Daniele De Marchi
7.2.1 Main issues .......................................................... 154
7.2.2 MRI: a complementary response to Echocardiography .......................................................... 155
7.2.3 Imaging strategies .................................................. 156
7.2.4 Sequences used for evaluation of cardiac function .... 159
7.2.5 Evaluation of the cardiac function with MR and postprocessing .................................................. 159
7.2.6 MRI quantification of left and right ventricular dimensions: accuracy and reproducibility ............... 162
7.2.7 Evaluation of diastolic function ............................... 164
7.2.8 Evaluation of cardiac function by tagging images ........................................................................ 166
References......................................................................... 168

7.3 Study of myocardium .................................................. 169
    Stress MRI ..................................................................... 169
    Alessandro Pingitore, Brunella Favilli, Petra Keilberg, Giovanni Aquaro, Elisabetta Strata
    References......................................................................... 182
7.3.2 Myocardial perfusion .............................................. 183
    Massimo Lombardi, Piero Ghedin
    References......................................................................... 192
7.3.3 Myocardial viability ............................................... 193
    Alessandro Pingitore, Brunella Favilli, Vincenzo Positano, Massimo Lombardi
    References......................................................................... 205
7.3.4 Cardiomyopathies .................................................. 209
    Massimo Lombardi, Claudia Raineri, Alessia Pepe
    References......................................................................... 231

7.4 Valvular disease......................................................... 236
    Massimo Lombardi
7.4.1 Introduction .......................................................... 236
7.4.2 Indications for MRI in valve disease................................. 237
7.4.3 Study of prosthetic valves................................................. 241
7.4.4 Current limitations............................................................. 241
7.4.5 Imaging procedure.............................................................. 242
References............................................................................... 243
7.5 Coronary arteries................................................................. 244
Alessandro Pingitore, Massimo Lombardi,
Paolo Marcheschi, Piero Ghedin
7.5.1 Introduction...................................................................... 244
7.5.2 Magnetic Resonance of coronaries:
angiographic approach......................................................... 244
7.5.3 How to improve SNR and CNR......................................... 248
7.5.4 Feasibility of coronary angiography by MR....................... 249
7.5.5 Study of the coronary wall by MRI................................. 250
7.5.6 Study of coronary reserve................................................. 251
7.5.7 Scanning planes for coronaries (in 2D or 3D
small slab).............................................................................. 253
7.5.8 Bypass and STENT........................................................... 254
7.5.9 Anomalies in the coursing of coronaries......................... 256
7.5.10 Conclusions.................................................................... 257
References............................................................................... 257
7.6 Tumors and masses of the heart
and of the pericardium .......................................................... 260
Virna Zampa, Massimo Lombardi
7.6.1 Introduction.................................................................... 260
7.6.2 Benign atrial tumors......................................................... 261
7.6.3 Benign ventricular tumors............................................... 266
7.6.4 Malignant tumors.............................................................. 266
7.6.5 Para-cardiac masses.......................................................... 269
7.6.6 Pitfall............................................................................... 271
References............................................................................... 272
7.7 Congenital heart disease ..................................................... 273
Pierluigi Festa
7.7.1 Introduction.................................................................... 273
7.7.2 Techniques....................................................................... 274
7.7.3 Cardiac MRI exam in congenital heart disease.............. 275
7.7.4 Extracardial defects of the mediastinal vessels.............. 277
7.7.5 Simple isolated cardiac defects....................................... 284
7.7.6 Defects of the atrio-ventricular connection.................... 288
7.7.7 Tronco-conal defects.......................................................... 290
7.7.8 Defects of the ventricular-arterial connections
(post surgery)......................................................................... 293
7.7.9 Complex defects (presurgery and postsurgery).............. 295
References............................................................................... 301
8 Pericardium and mediastinum ........................................................ 303
  Virna Zampa, Giulia Granai, Paola Vagli..........................................

  8.1 Pericardium ................................................................. 303
  8.1.1 Introduction .......................................................... 303
  8.1.2 Normal anatomy .................................................... 303
  8.1.3 Congenital disease ................................................. 304
  8.1.4 Pericardial effusion ................................................. 306
  8.1.5 Constrictive pericarditis .......................................... 306
  8.1.6 Hematoma .............................................................. 307
  8.2 Mediastinum .............................................................. 309

  8.2.1 Introduction .......................................................... 309
  8.2.2 Technological and methodological aspects .................... 309
  8.2.3 Clinical applications ............................................... 310

References.................................................................................. 318

9 Thoracic aorta......................................................................... 319
  Massimo Lombardi

  9.1 Introduction ................................................................... 319
  9.2 Patient preparation ...................................................... 320
  9.3 Imaging techniques ..................................................... 320
  9.4 Data processing .......................................................... 325
  9.5 Acquired pathologies of the thoracic aorta ....................... 327
  9.5.1 Aneurysms of the aorta ............................................ 327
  9.5.2 Aortic dissection .................................................... 329
  9.5.3 Aortic intramural hematoma and ulcer
      of the aortic wall ........................................................ 330
  9.5.4 Traumas of the aorta ............................................... 331
  9.5.5 Follow-up of aortic disease ..................................... 331
  9.5.6 Aortitis ..................................................................... 334
  9.6 Limits of the technique ................................................ 335
  9.7 Conclusions ................................................................... 335

References.................................................................................. 337

10 Renal arteries ....................................................................... 339
  Mirco Cosottini, Maria Chiara Michelassi, Guido Lazzarotti

  10.1 Introduction ................................................................... 339
  10.2 MRA techniques ........................................................ 341
  10.2.1 Time Of Flight MRA (TOF-MRA) .............................. 341
  10.2.2 Phase Contrast MRA (PC-MRA) ............................... 341
  10.2.3 Contrast Enhanced MRA (CEMRA) ......................... 344
  10.3 Technical features ..................................................... 346
  10.4 Clinical applications ................................................... 346
  10.4.1 Stenosing pathologies ............................................. 346
## 11 Abdominal aorta ......................................................... 357

Virna Zampa, Marzio Perri, Simona Ortori

11.1 The technique ............................................................. 357
11.1.1 Ultrafast technique with contrast bolus ......................... 357
11.1.2 Phase Contrast MRA (PC-MRA) .................................... 360
11.2 Clinical applications ................................................... 361
11.2.1 Atherosclerotic and inflammatory aneurysms .................. 361
11.2.2 Dissection ................................................................. 366
11.2.3 Steno-occlusion ......................................................... 368
11.2.4 Control of vascular stents/prostheses ............................ 370
11.2.5 Retroperitoneal fibrosis ............................................... 373

References ........................................................................ 374

## 12 Peripheral arterial system ............................................. 377

Virna Zampa, Irene Bargellini

12.1 Introduction ................................................................. 377
12.2 Technique ................................................................. 378
12.2.1 Patient preparation .................................................... 378
12.2.2 Time Of Flight Angio-MR (TOF-MRA) ......................... 378
12.2.3 Contrast Enhanced MRA (CEMRA) ............................... 380
12.3 Clinical applications .................................................... 385
12.3.1 Atherosclerosis ......................................................... 385
12.3.2 Surgical arterial bypass .............................................. 387
12.3.3 Vascular lesions of the soft tissue and vascularization of tumoral lesions ........................................... 387
12.3.4 Obstructive pathology due to external compression ....... 389
12.4 Advantages ................................................................. 389
12.5 Limits ........................................................................... 390
12.5.1 Timing ....................................................................... 390
12.5.2 Artifacts .................................................................... 391
12.5.3 Visualizing the vascular lumen alone ............................ 391
12.5.4 Missed visualization of arteries not included in the volume of study .............................................. 392
12.5.5 Missed dynamic visualization ..................................... 392
12.5.6 Localizing a lesion ..................................................... 393
12.6 Conclusions ................................................................. 393

References ........................................................................ 393
List of Contributors

GIOVANNI AQUARO
MRI Laboratory
CNR, Institute of Clinical Physiology,
Pisa, Italy

IRENE BARGELLINI
Diagnostic and Interventional
Radiology
University, AOUP, Pisa, Italy

RAFFAELLO CANAPICCHI
MRI Laboratory
CNR, Institute of Clinical Physiology,
Pisa, Italy

MIRCO COSOTTINI
Department of Neuroscience
University of Pisa
and Diagnostic and Interventional
Radiology
University, AOUP, Pisa, Italy

MARIOLINA DEIANA
MRI Laboratory
CNR, Institute of Clinical Physiology,
Pisa, Italy

DANIELE DE MARCHI
MRI Laboratory
CNR, Institute of Clinical Physiology,
Pisa, Italy

BRUNELLA FAVILLI
MRI Laboratory
CNR, Institute of Clinical Physiology,
Pisa, Italy

PIERLUIGI FESTA
MRI Laboratory
CNR, Institute of Clinical Physiology,
Pisa, Italy

PIERO GHEDIN
GE Healthcare
Milan, Italy

GIULIA GRANAI
Diagnostic and Interventional
Radiology
University, AOUP, Pisa, Italy

PETRA KEILBERG
MRI Laboratory
CNR, Institute of Clinical Physiology,
Pisa, Italy

GUIDO LAZZAROTTI
Diagnostic and Interventional
Radiology
University, AOUP, Pisa, Italy

MASSIMO LOMBARDI
MRI Laboratory
CNR, Institute of Clinical Physiology,
Pisa, Italy
List of Contributors

FRANCESCO LOMBARDO  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

PAOLO MARCHESCHI  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

MARIA CHIARA MICHELASSI  
Diagnostic and Interventional Radiology  
University, AOUP, Pisa, Italy

DOMENICO MONTANARO  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

LORENZO MONTI  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

SIMONA ORTORI  
Diagnostic and Interventional Radiology  
University, AOUP, Pisa, Italy

ALESSIA PEPE  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

MARZIO PERRI  
Diagnostic and Interventional Radiology  
University, AOUP, Pisa, Italy

ALESSANDRO PINGITORE  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

VINCENZO POSITANO  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

CLAUDIA RAINERI  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

MARIA FILOMENA SANTARELLI  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

FABIO SCAZZERI  
UO Neuroradiology Ospedale Civile  
Livorno, Italy

ANNA MARIA SIRONI  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

ELISABETTA STRATA  
MRI Laboratory  
CNR, Institute of Clinical Physiology, Pisa, Italy

PAOLA VAGLI  
Diagnostic and Interventional Radiology  
University, AOUP, Pisa, Italy

VIRNA ZAMPA  
Diagnostic and Interventional Radiology  
University, AOUP, Pisa, Italy
List of Acronyms

ACR  American College of Radiology
AFP  Alfa Feto Protein
AHA  American Heart Association
AO   Aorta
AoCo Aortic Coarctation
APVR Anomalous Pulmonary Venous Return
ARVC Arrhythmogenic Right Ventricle Cardiomyopathy
ASD  Atrial Septal Defect
AVC  Atrio Ventricular Connection
AVM  Artero-Venous Malformations
A1   Anterior cerebral a.
β-HCG Beta-Human Chorionic Gonadotropin
BSA  Body Surface Area
CA   Cavernous Angiomas
CCD  Charging coupling device
CDP  Complex Difference Processing
CDROM Compact Disk Read Only Memory
CEMRA Contrast Enhanced Magnetic Resonance Angiography
CHESS Chemical shift selective
c.m. Contrast Medium
CNR  Contrast-to-Noise Ratio
CP-MRA Contrast Phase Magnetic Resonance Angiography
CT   Capillary Telangiectasias
CT   Circulation Time
CT   Computed Tomography
CVT  Cerebral Venous Thrombosis
CX   Circumflex Coronary a.
DAF  Dural Artero-venous Fistula
DAT  Digital Audio Tape
DCCF Direct Carotid-Cavernous Fistula
DE   Delayed-contrast Enhancement
DFT  Discrete Fourier Transform
DICOM Digital Imaging and Communication in Medicine
DSA  Digital Subtraction Angiography
DVD  Digital Video Disk
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVDROM</td>
<td>Digital Video Disk Read Only Memory</td>
</tr>
<tr>
<td>DY-DTPA-BMA</td>
<td>Dysprosium diethylene triamine pentaacetic acid-bismethylamide</td>
</tr>
<tr>
<td>EBT</td>
<td>Electron Beam Tomography</td>
</tr>
<tr>
<td>ECD</td>
<td>Echo Color Doppler</td>
</tr>
<tr>
<td>ECD</td>
<td>Endocardial Cushions Defect</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiography</td>
</tr>
<tr>
<td>EDV</td>
<td>End Diastolic Volume</td>
</tr>
<tr>
<td>EF</td>
<td>Ejection Fraction</td>
</tr>
<tr>
<td>EPI</td>
<td>Echo Planar Imaging</td>
</tr>
<tr>
<td>ESV</td>
<td>End Systolic Volume</td>
</tr>
<tr>
<td>FA</td>
<td>Flip Angle</td>
</tr>
<tr>
<td>FDG</td>
<td>18-Fluorodeoxyglucose</td>
</tr>
<tr>
<td>FFE</td>
<td>Fast Field Echo</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FGRE</td>
<td>Fast Gradient Echo</td>
</tr>
<tr>
<td>FID</td>
<td>Free Induction Decay</td>
</tr>
<tr>
<td>FIESTA</td>
<td>Fast Imaging Employing Steady-State Acquisition</td>
</tr>
<tr>
<td>FIS</td>
<td>Free Induction Signal</td>
</tr>
<tr>
<td>FISP</td>
<td>Fast Imaging with Steady-state free Precession</td>
</tr>
<tr>
<td>FLAIR</td>
<td>Fluid Attenuated Inversion Recovery</td>
</tr>
<tr>
<td>FLASH</td>
<td>Fast Low Angle Shot</td>
</tr>
<tr>
<td>FOV</td>
<td>Field Of View</td>
</tr>
<tr>
<td>FS</td>
<td>Fat Suppression</td>
</tr>
<tr>
<td>FSE</td>
<td>Fast Spin Echo</td>
</tr>
<tr>
<td>FSE-IR</td>
<td>Fast Spin Echo – Inversion Recovery</td>
</tr>
<tr>
<td>FT</td>
<td>Fallot’s Tetralogy</td>
</tr>
<tr>
<td>Gd</td>
<td>Gadolinium</td>
</tr>
<tr>
<td>Gd-DTPA</td>
<td>Gadolinium-diethylene triamine pentaacetic acid</td>
</tr>
<tr>
<td>Gd-DTPA-BMA</td>
<td>Gadolinium-diethylene triamine pentaacetic acid-bismethylamide</td>
</tr>
<tr>
<td>Gd-HP-DO3A</td>
<td>Gadolinium 1,4,7-tris(carboxymethyl)-10-(2’-hydroxypropyl)-1,4,7,10-tetraaza cyclododecane</td>
</tr>
<tr>
<td>GRASS</td>
<td>Gradient Recalled Acquisition in Steady State</td>
</tr>
<tr>
<td>GRE</td>
<td>Gradient Echo</td>
</tr>
<tr>
<td>G-SPECT</td>
<td>Gated-Single Photon Emission Computed Tomography</td>
</tr>
<tr>
<td>HARP</td>
<td>HARmonic Analysis of Phase</td>
</tr>
<tr>
<td>HCM</td>
<td>Hypertrophic Cardiomyopathy</td>
</tr>
<tr>
<td>HU</td>
<td>Hounsfield Unit</td>
</tr>
<tr>
<td>IAD</td>
<td>Interatrial Defect</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>IR</td>
<td>Inversion Recovery</td>
</tr>
<tr>
<td>IR-GRE</td>
<td>Inversion-Recovery Gradient Echo</td>
</tr>
<tr>
<td>IR-GRE DE</td>
<td>Inversion-Recovery Gradient Echo Delayed Enhancement</td>
</tr>
<tr>
<td>IT</td>
<td>Inversion delay Time</td>
</tr>
<tr>
<td>IV</td>
<td>Innominate Vein</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>IVC</td>
<td>Inferior Vena Cava</td>
</tr>
<tr>
<td>JIRA</td>
<td>Japan Industries Association Radiological systems</td>
</tr>
<tr>
<td>LA</td>
<td>Left Atrium</td>
</tr>
<tr>
<td>LAD</td>
<td>Left Anterior Descending a.</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LM</td>
<td>Left Main a.</td>
</tr>
<tr>
<td>LPA</td>
<td>Left Pulmonary Artery</td>
</tr>
<tr>
<td>LPV</td>
<td>Left Pulmonary Vein</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
</tr>
<tr>
<td>LV</td>
<td>Left Ventricle</td>
</tr>
<tr>
<td>MEDICOM</td>
<td>Medical Products Electronic Commerce</td>
</tr>
<tr>
<td>MEDICOM</td>
<td>MEdia Interchange COMunication</td>
</tr>
<tr>
<td>MIP</td>
<td>Maximum Intensity Projection</td>
</tr>
<tr>
<td>Mn-DPDP</td>
<td>Manganese-dipyridoxal diphosphate</td>
</tr>
<tr>
<td>MOTSA</td>
<td>Multiple Overlapping Thin-Slab Acquisition</td>
</tr>
<tr>
<td>MPR</td>
<td>Multiplanar Reconstruction</td>
</tr>
<tr>
<td>MPA</td>
<td>Main Pulmonary Artery</td>
</tr>
<tr>
<td>MPVR</td>
<td>Multiplanar Volume Reconstruction</td>
</tr>
<tr>
<td>MR</td>
<td>Magnetic Resonance</td>
</tr>
<tr>
<td>MRA</td>
<td>Magnetic Resonance Angiography</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>MT</td>
<td>Magnetization Transfer</td>
</tr>
<tr>
<td>MTT</td>
<td>Mean Transit Time</td>
</tr>
<tr>
<td>NASCET</td>
<td>North American Symptomatic Carotid Endoarterectomy Trial</td>
</tr>
<tr>
<td>NEMA</td>
<td>National Electrical Manufacturers Association</td>
</tr>
<tr>
<td>NEX</td>
<td>Number of Excitations</td>
</tr>
<tr>
<td>NVC</td>
<td>Neuro Vascular Conflict</td>
</tr>
<tr>
<td>PA</td>
<td>Pulmonary Artery</td>
</tr>
<tr>
<td>PAPVR</td>
<td>Partial Anomalous Pulmonary Venous Return</td>
</tr>
<tr>
<td>PC</td>
<td>Phase Contrast</td>
</tr>
<tr>
<td>PD</td>
<td>Proton Density</td>
</tr>
<tr>
<td>PDP</td>
<td>Phase Difference Processing</td>
</tr>
<tr>
<td>PDW</td>
<td>Proton Density Weight</td>
</tr>
<tr>
<td>PET</td>
<td>Positron Emission Tomography</td>
</tr>
<tr>
<td>PFR</td>
<td>Peak Filling Rate</td>
</tr>
<tr>
<td>PCr/ATP</td>
<td>Phospho Creatine/Adenosine Triphosphate</td>
</tr>
<tr>
<td>PICA</td>
<td>Postero Inferior Cerebellar Artery</td>
</tr>
<tr>
<td>PTA</td>
<td>Percutaneous Transluminal Angioplasty</td>
</tr>
<tr>
<td>PVC-MRI</td>
<td>Phase Velocity Cine Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>QP/QS</td>
<td>Pulmonary Flow/ Systemic Flow</td>
</tr>
<tr>
<td>RA</td>
<td>Right Atrium</td>
</tr>
<tr>
<td>RC</td>
<td>Right Coronary</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RES</td>
<td>Reticuloendothelial system</td>
</tr>
<tr>
<td>REV</td>
<td>Réparation à l’Etage Ventrriculaire</td>
</tr>
<tr>
<td>RIPV</td>
<td>Right Inferior Pulmonary Vein</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>ROI</td>
<td>Region Of Interest</td>
</tr>
<tr>
<td>RPA</td>
<td>Right Pulmonary Artery</td>
</tr>
<tr>
<td>RV</td>
<td>Right Ventricle</td>
</tr>
<tr>
<td>SA</td>
<td>Saccular Aneurysms</td>
</tr>
<tr>
<td>SVC</td>
<td>Superior Vena Cava</td>
</tr>
<tr>
<td>SE</td>
<td>Spin Echo</td>
</tr>
<tr>
<td>SENSE</td>
<td>SENSitivity Encoding techniques</td>
</tr>
<tr>
<td>SMASH</td>
<td>Simultaneous Acquisition of Spatial Harmonics</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SPECT</td>
<td>Single Photon Emission Computed Tomography</td>
</tr>
<tr>
<td>SPGR</td>
<td>SPoiled Gradient Echo</td>
</tr>
<tr>
<td>SPGR-ET</td>
<td>SPoiled Gradient Echo Train</td>
</tr>
<tr>
<td>SSFP</td>
<td>Steady State Free Precession (Fiesta, True FISP, Balanced Echo)</td>
</tr>
<tr>
<td>STIR</td>
<td>Short Time Inversion Recovery</td>
</tr>
<tr>
<td>SV</td>
<td>Stroke Volume</td>
</tr>
<tr>
<td>T1</td>
<td>Longitudinal relaxation time</td>
</tr>
<tr>
<td>T2</td>
<td>Transverse relaxation time</td>
</tr>
<tr>
<td>TA</td>
<td>Time of Acquisition</td>
</tr>
<tr>
<td>TAPVR</td>
<td>Total Anomalous Pulmonary Venous Return</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>TE</td>
<td>Time to Echo</td>
</tr>
<tr>
<td>TEA</td>
<td>Thromboendoarterectomy</td>
</tr>
<tr>
<td>TEE</td>
<td>Transesophageal Echography</td>
</tr>
<tr>
<td>TF</td>
<td>Tetralogy of Fallot</td>
</tr>
<tr>
<td>TGA</td>
<td>Transposition of Great Arteries</td>
</tr>
<tr>
<td>TIMI</td>
<td>Thrombolysis In Myocardial Infarction</td>
</tr>
<tr>
<td>TI</td>
<td>Time of Inversion</td>
</tr>
<tr>
<td>TOF</td>
<td>Time Of Flight</td>
</tr>
<tr>
<td>TOS</td>
<td>Thoracic Outlet Syndrome</td>
</tr>
<tr>
<td>TR</td>
<td>Time of Repetition</td>
</tr>
<tr>
<td>TRICKS</td>
<td>Time Resolved Imaging of Contrast Kinetics</td>
</tr>
<tr>
<td>TTE</td>
<td>Trans Thoracic Echocardiography</td>
</tr>
<tr>
<td>USPIO</td>
<td>Ultrasmall Superparamagnetic Iron Oxide</td>
</tr>
<tr>
<td>VENC</td>
<td>Velocity Encoding</td>
</tr>
<tr>
<td>VA</td>
<td>Venous Angiomas</td>
</tr>
<tr>
<td>VD</td>
<td>Venous Dysplasia</td>
</tr>
<tr>
<td>VSD</td>
<td>Ventricular Septal Defect</td>
</tr>
<tr>
<td>WMSI</td>
<td>Wall Motion Score Index</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
<tr>
<td>2D</td>
<td>Bi-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
</tbody>
</table>
1 Physical principles of imaging with magnetic resonance

MARIA FLOMENA SANTARELLI

1.1 Introduction

Magnetic Resonance (MR) is a phenomenon involving magnetic fields and electromagnetic waves on the Radio Frequency (RF) domain. The discovery of this phenomenon is quite recent and was simultaneously made in 1946 by two independent groups of investigators at Stanford (directed by Bloch) and at Harvard (headed by Purcell) [1, 2]. Since its discovery, MR has become very popular, being an extremely useful tool, especially in the fields of analytical chemistry and biochemistry [3, 4].

The intuition of using MR on humans came from experiments by Jackson, who in 1967 acquired the first MR signals from a live animal. In 1972, Lauterbur [5] obtained the first MR image from a sample containing water and two years later generated the very first image from a live animal [6]. Later, many other groups, more or less independently, contributed to improving the technique toward those technologies that would allow the generation and reconstruction of MR images [7-12]. Magnetic Resonance Imaging (MRI) allows to generate images that yield excellent contrast between soft tissues, with high spatial resolution in each direction. Like other imaging techniques, MRI also employs electromagnetic radiation to examine the districts inside the human body; however, because it employs low energy radiation, it may be considered non-hazardous when used within tested limits.

In this chapter we will introduce the basic principles underlying the phenomenon of MR and the formation of MR images. The description of the single processes is not meant to be exhaustive. Because many of the principles we will deal with here are quite complex, we have put particular effort in keeping explanations simple avoiding details that would take the reader away from the main train of thought. For more exhaustive explanations on single processes or phenomena we suggest a list of specialist readings [13-16], while the principles of MR and their application to the cardiovascular system can be found on specific text books [17, 18].

1.2 The phenomenon of magnetic resonance

The phenomenon of Magnetic Resonance may be approached using different types of nuclei (\(^1\)H, \(^{13}\)C, \(^{19}\)F, \(^{23}\)Na, \(^{31}\)P), however the atom \(^1\)H is generally uti-
lized for creating MR images. To get an idea of what nuclear magnetism is, we can imagine a similarity with an electrically charged mass rotating on its own axis that generates a tiny magnetic field with its own direction and orientation. This phenomenon is the so-called “spin” and is what attributes the magnetic momentum \( m \) to the nucleus (Fig. 1.1).

In the case of \(^1\text{H}\), the nucleus is composed of a single proton (positive electric charge).

### 1.2.1 The nucleus

The property that allows each nucleus to interact with a magnetic field is the so-called intrinsic spin. It is a quantum phenomenon according to which the nucleus rotates on its axis, as illustrated in Figure 1.1. The values taken by the spin, \( I \), depend on the number of protons and neutrons inside the nucleus.

If \( I = 0 \), there is no interaction between the nucleus and the external magnetic field. The atom of hydrogen \(^1\text{H}\) has a single proton and its spin is \( I = 1/2 \).

The angular momentum, \( p \), given by the spin \( I \) is given by:

\[
p = \hbar \ I
\]

where \( \hbar \) is Planck’s constant; \( p \) and \( I \) are vectors.

The so-called gyromagnetic ratio links the magnetic momentum \( \mu \) to the angular momentum \( p \):

\[
\gamma = \frac{\mu}{p}
\]

The value is a constant characteristic of the type of nucleus; for example, \( \gamma \) for \(^1\text{H}\), is 42.57 MHz/T (MHz: MegaHertz; T: Tesla).
1.3 Interaction with an external magnetic field

We can imagine the nucleus of hydrogen $^1\text{H}$ as a magnetic bar with a north and south pole (bipolar). According to the laws of quantum mechanics, the momentum of the dipole can take on the values of $2I+1$ orientations in an external magnetic field, corresponding to the $2I+1$ energy levels allowed. The “magnetic bar”, the proton, can thus align with the external field in parallel or anti-parallel position, as represented in Figure 1.2.

In fact, the quantum model should be used to explain all the phenomena of nuclear magnetic resonance. However, from an intuitive point of view, the classical model in which the spin can assume any position in the external magnetic field shows to be the best for visualizing most of the experiments.

For $I = 1/2$, as in the nucleus of hydrogen, all the predictions of the classical model are in exact agreement with the quantum theory applied to a macroscopic system.

In the classical model, an electrically charged mass rotating on its axis will tend to align itself with $B_0$ when immersed in the magnetic field $B_0$. Thus the proton is affected by a rotating force that induces the proton to start precessing on $B_0$.

This could be compared to the spinning top that rotates on itself, moving with precessional motion about an axis perpendicular to the floor (force of gravity).

The precession rate (the number of rotations around the direction of $B_0$ over the unit of time) depends on the type of nucleus and the intensity of $B_0$.

The precession frequency can be calculated by means of Larmor’s law:

$$\omega = \gamma B_0$$

where $\omega$ is the so-called “Larmor frequency” (measured in MHz); $\gamma$ is the gyro-magnetic ratio (measured in MHz/Tesla, that describes the relationship of mechanical and magnetic properties of the nucleus considered and depends on the type of nucleus); $B_0$ is the intensity of the magnetic field in which the nucleus is immersed [(measured in Tesla T, where $1.0T = 10 \text{ kG} = 10.000 \text{ G (Gauss)}$)].

Fig. 1.2. Spin energy levels in a magnetic field; left: low energetic level, right: high energetic level
Formula (3) indicates that by increasing the intensity of the magnetic field $B_0$, the frequency $\omega$ increases and thus also the nucleus rotation rate around $B_0$. In reality, a single nucleus or a single magnetic momentum cannot be observed, but the combined effect of all the nuclei within a sample can be. What can be observed is thus the total magnetization $M$, given by the vectorial summation of the single magnetic moments: $M = \sum \mu$, as shown in Figure 1.3.

Because magnetic moments tend to align each other to the magnetic field, there is only one component along $B_0$ at equilibrium.

1.3.1 Radio Frequency (RF) pulses

To evaluate the total magnetization, we must find a way of perturbing the system in its equilibrium state and force $M$ to move away from $B_0$. Hence an excitation pulse is given by applying a second magnetic field $B_1$, which is perpendicular to $B_0$ and rotates around $B_0$ at a rate $\omega$, exactly the same as the precession frequency of the nuclei.

The field $B_1$ causes $M$ to move from its resting position, parallel to $B_0$, forcing $M$ to take a spiral trajectory, Figure 1.4.

When $B_1$ is switched off, $M$ continues precessing, describing a cone with an angle $\alpha$ to $B_0$.

The amplitude of this angle, the flip angle, depends on the amplitude of $B_1$ and on the duration of its application.

In fact:

$$\alpha = \gamma B_1 t$$

where $t$ is the time during which the field $B_1$ is left on.

If $B_1$ is applied for sufficient time, it can cause $M$ to position at 90° with respect to $B_0$. In such a case, the application of $B_1$ is called a 90° pulse. $M$ may
be also positioned in direction $-B_0$, which is called 180° pulse or inversion pulse.

Because $\omega/2\pi$ normally ranges between 1 MHz and 500 MHz (frequencies that fall within the radio frequency domain), $B_1$ pulses are also known as radio frequency pulses and $B_1$ as radio frequency magnetic field.

### 1.3.2 Free Induction Decay (FID)

After a 90° pulse has been applied, the magnetization vector $M$ itself generates an oscillating RF magnetic field, which can be detected in virtue of the alternated current it produces in a coil – in this case the same coil used to apply the $B_1$ field. The signal induced by the magnetization vector increases during the 90° pulse and decays to zero after the pulse is switched off because of the relaxation that makes $M$ return to its original equilibrium position $M_0$, parallel to $B_0$.

This type of decay signal obtained in absence of $B_1$, is called Free Induction Decay (FID), or Free Induction Signal (FIS), Figure 1.5. In this text we will refer to it as the FID MR signal.

#### 1.3.2.1 The rotating reference system

What we are interested in here, is the behavior of the magnetization vector during the pulse sequences. The movement of the aforementioned vector $M$ is quite complicated and difficult to visualize when considering all the involved phenomena together, especially when one or two pulses are applied. In order to facilitate the mathematical and visual description of the phenom-
enon, it is best to describe it from the view of an observer who is rotating on an axis parallel to $B_0$, in synchrony with nuclear magnetic moments. This is the so-called “rotating reference system”.

It is like observing moving objects from a rotating merry-go-round: if we are exclusively interested in the movement of the objects and not in the rotating merry-go-round, it is easier for us to observe it by being on the ride rotating with those object, than being in a fixed point on the ground.

Observing the objects being on the ground is the so called “static reference system”, while observing the objects being on the merry-go-round is the “rotating reference system”.

In the case of the rotating system, the protons precessing with $\omega$ frequency are still, while those protons that for some additional phenomenon (as we shall see later) precess at a minor speed are seen as rotating counterclockwise; likewise, the protons precessing at a speed higher than $\omega$ are seen as rotating clockwise (Fig. 1.6).
1.4 Magnetic Resonance interaction with tissues

The contrast in the images of nuclear magnetic resonance depends on the different magnetic properties of the tissues. Although many parameters influence the signal coming from a sample under observation, the most commonly used are: proton density, T1 and T2, which are derived from the MR signal released from the material. These parameters may have different values for different tissues, but also have different values within the same tissue according to whether it is in a normal or diseased state.

1.4.1 Proton density

Most of the hydrogen molecules in the human body are bound in the molecules of water and fat, which is what we search for in the experiments of MR.

The term proton density simply refers to the number of protons per volume unit. Therefore, accordingly with the water contents, proton density in bones is low, high in liver, and very high in blood.

The proton density for a tissue examined is basically proportional to the initial amplitude of the MR signal immediately following the end of 90° excitation pulse (Fig. 1.7): the higher the proton density, the higher the amplitude of the signal.

1.4.2 Relaxation

The relaxation of the spin is caused by the exchange of energy between spins and between spins and the surrounding environment. These interactions generate two kinds of decay of the M vector, which are called spin-spin relaxation and spin-lattice relaxation. The result of relaxation is the return of M to its equilibrium state parallel to B₀.

Fig. 1.7. Effect of the different proton density on the M₀ vector and on signal intensity
Spin-spin relaxation

The spin-spin relaxation, also said transversal relaxation, or T2, is caused by the interaction between nuclear magnetic moments.

The magnetic field experimented in each instant by each nucleus is certainly dominated by the external field applied, however there is an additional contribution to the local field on behalf of the closer neighboring nuclei. These spin-spin interactions cause a weak change in the precessing frequencies of each nucleus. The result is a loss in phase coherence among the nuclei, with a reduction in the transverse component of the magnetization vector $\mathbf{M}$ ($M_{xy}$) – that is the component perpendicular to the field $\mathbf{B}_0$ (Fig. 1.8). The constant of the transverse relaxation time $M_{xy}$ is given by $T_2$, that is the time necessary to reduce spin-lattice relaxation of the transverse component $M_{xy}$ by 63%.

Spin-lattice relaxation

The spin-lattice relaxation, also called longitudinal relaxation time or $T_1$, causes a gradual realignment of the magnetic moments with $\mathbf{B}_0$, as shown in Figure 1.9. This phenomenon depends on the intrinsic properties of the nucleus but also on the microenvironment in which the nucleus is immersed (surrounding nuclei, temperature, presence of large-sized molecules, paramagnetic molecules as those of contrast media, and so on) – from here the reference to spin-lattice interaction. Hence, the longitudinal component of $\mathbf{M}$ returns to the equilibrium value $M_0$ within a characteristic time, $T_1$. $T_1$ is the time needed for 63% of $\mathbf{M}$ to return to equilibrium $M_0$ after a 90° RF pulse.